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KNOCK-LIMITED PERFORMANCE OF PURE HYDROCARBONS BLENDED
WITH A BASE FUEL IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER

III - FOUR AROMATICS, SIX ETHERS

By Anthony W. Jones, Arthur W. Bull, and Edmund R. Jonash

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NACA

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KNOCK-LIMITED PERFORMANCE OF PURE HYDROCARBONS BLENDED WITH

A BASE FUEL IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER

III -FOUR AROMATICS, SIX ETHERS

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SUMMARY

Knock-limited performance tests of leaded blends of four pure aromatic hydrocarbons and six pure ethers with a base fuel were conducted in a full-scale aircraft-engine cylinder at two operating conditions to determine the antiknock effectiveness of additions of pure compounds to aviation fuels. The following fuels were tested:

- n-Butylbenzene
- Isobutylbenzene
- n-Propylbenzene
- 1-Isopropyl-4-methylbenzene (p-cymene)
- Methyl tert-butyl ether
- Ethyl tert-butyl ether
- Isopropyl tert-butyl ether
- Methyl phenyl ether (anisole)
- Ethyl phenyl ether (phenetole)
- Methyl p-tolyl ether

Each of these fuels was blended with a base fuel (87½ percent S-4 and 12½ percent n-heptane plus 4 ml TEL/gal) and the final blend was leaded to 4.0 ml TEL per gallon. The four aromatics were blended to a concentration of 25 percent by volume and the ethers were blended to a concentration of 10 percent by volume in the base fuel. The base fuel and a fuel consisting of 85 percent S-4 and 15 percent M-4 plus 4.0 ml TEL per gallon were also tested separately. Curves of S-4 reference fuels having lead concentrations up to 4.0 ml TEL per gallon were obtained to bracket most of the test-fuel curves.

The data obtained from knock tests on a full-scale aircraft-engine cylinder indicate that:

1. The four aromatic hydrocarbons increased the knock limit of the base fuel at both operating conditions and p-cymene gave the greatest increase at all conditions with the exception of isobutylbenzene, which developed equivalent power in the lean region (0.06 to 0.075 fuel-air ratio) under the modified CRC cruise conditions.

2. The six ethers increased the knock-limited power of the base fuel at both operating conditions. Methyl tert-butyl ether gave the greatest increase throughout the normal fuel-air-ratio range at the CRC cruise conditions. Methyl tert-butyl ether also gave the greatest improvement at the modified cruise conditions except at fuel-air ratios leaner than 0.065 where ethyl tert-butyl ether gave an equivalent increase in knock-limited performance.

INTRODUCTION

A general investigation to determine the antiknock effectiveness of additions of pure hydrocarbons and other pure compounds to aircraft-engine fuels is being conducted by the NACA Cleveland laboratory. The program includes tests with 17.6, F-3 and F-4 small-scale engines, and a full-scale aircraft-engine cylinder. The knock-limited performance of 8 pure paraffins, 2 pure olefins, and 12 pure aromatics blended and leaded with a base fuel tested in a full-scale aircraft-engine cylinder are reported in references 1 and 2.

The present report gives the results of knock tests with leaded blends of four pure aromatic hydrocarbons and six pure ethers with a base fuel at two operating conditions. These tests were run between February and May 1945 in an aircraft-engine cylinder. F-3 ratings of all the blends and F-4 ratings of the aromatic blends are included in this report.

FUELS

The Organic Synthesis Section of the Cleveland laboratory prepared for the full-scale single-cylinder tests small quantities (5 gal of each of the aromatics, 3 gal of each of the ethers) of the following pure fuels leaded to a concentration of 4.0 ml TEL per gallon:

n-Butylbenzene
Isobutylbenzene
n-Propylbenzene
1-Isopropyl-4-methylbenzene (p-cymene)
Methyl tert-butyl ether
Ethyl tert-butyl ether
Isopropyl tert-butyl ether
Methyl phenyl ether (anisole)
Ethyl phenyl ether (phenetole)
Methyl p-tolyl ether

The four leaded aromatic hydrocarbons were mixed with the base fuel to form blends containing 25 percent by volume hydrocarbon and 75 percent by volume base fuel and the leaded ethers were mixed with the base fuel to form 10-percent blends by volume.

The base fuel consisted of $87\frac{1}{2}$ percent S-4 reference fuel and $12\frac{1}{2}$ percent n-heptane leaded to a concentration of 4.0 ml TEL per gallon and was inhibited with 0.09 pound of inhibitor per 500 gallons of fuel. The base fuel used in these tests differed from the base fuel used in previous tests (references 1 and 2) in that only pure paraffinic compounds were used. The original base fuel (references 1 and 2), which consisted of 85 percent S-4 reference fuel and 15 percent M-4 reference fuel leaded to a concentration of 4.0 ml TEL per gallon, was not used because the small amount of aromatics (about 8 percent by volume) present in the M-4 reference-fuel component of the blend might have some undesirable effect. A knock-limited power level equivalent to the original base fuel was desired and tests on an F-4 engine showed that the blend of $87\frac{1}{2}$ percent S-4 reference fuel and $12\frac{1}{2}$ percent n-heptane plus 4.0 ml TEL per gallon met this specification.

The reference fuels used to bracket most of the test fuels were:

S-4
S-4 plus 0.5 ml TEL per gallon
S-4 plus 1.25 ml TEL per gallon
S-4 plus 2.5 ml TEL per gallon
S-4 plus 4.0 ml TEL per gallon

APPARATUS AND METHODS

Apparatus. - The tests were conducted on a full-scale air-cooled cylinder mounted on a CUE crankcase. The auxiliary apparatus used in these tests was the same as that used in reference 1 except that a heat exchanger was installed in the cooling-air line to control the cooling-air temperature and the exhaust system was modified to permit engine operation at either atmospheric exhaust pressure or at a reduced exhaust pressure.

A full-scale aircraft-engine cylinder with a displacement of 202 cubic inches was used for the tests; the engine conditions were:

	CRC simu- lated cruise	Modified CRC sim- ulated cruise
Inlet-air temperature, °F	210	250
Spark advance, deg B.T.C. (both plugs)	20	30
Exhaust pressure, inches of mercury absolute	29 ± 0.5	15 ± 0.2
Compression ratio	7.3	7.3
Engine speed, rpm	2000	2000
Oil flow to piston jets, pounds per minute	8	8
Fuel temperature at entrance to injection pump, °F	60 to 80	60 to 80
Cooling-air temperature, °F	80 ± 3	80 ± 3
Valve timing:		
Intake opens, deg B.T.C.	15	15
Intake closes, deg A.B.C.	44	44
Exhaust opens, deg B.B.C.	74	74
Exhaust closes, deg A.T.C.	25	25

The exhaust pressure of 15 inches of mercury was chosen because data from this laboratory show the existence of a critical relation between manifold and exhaust pressures and knock-limited power in the lean region where the manifold pressure is within +10 or -5 inches mercury of the exhaust pressure. The advanced spark and increased inlet-air temperature were chosen in an effort to obtain a more severe operating condition than the normal CRC cruise rating.

The cooling-air flow was determined for each test by operating the engine at a brake mean effective pressure of 140 pounds per square inch and a fuel-air ratio of 0.10 and by adjusting the damper valve in the cooling-air line until a rear spark-plug-bushing

temperature of 365° F was reached. The cooling-air pressure drop across the cylinder thus determined was maintained constant for each test.

Knock was detected with a magnetostriction pickup unit inserted into the combustion chamber and used in conjunction with a cathode-ray oscillograph.

Test procedure. - In order to obtain complete mixture-response curves with the limited amount of fuel blends available, the special procedures described in reference 1 were used at both operating conditions.

Engine conditions were checked before each test-fuel run by obtaining four or five knock points with the blend of 85 percent S-4 reference fuel and 15 percent M-4 reference fuel plus 4.0 ml TEL per gallon.

Mixture-response curves for the reference fuels were determined at both operating conditions to bracket most of the test fuels. Friction runs were made after each test.

Precision of tests. - The variation of the knock-limited indicated mean effective pressure of the fuel blend (85 percent S-4 and 15 percent M-4 plus 4 ml TEL/gal) used for checking engine conditions from day to day is shown in figure 1. The daily variation in engine behavior was comparable with that observed in reference 1 and smaller than that observed in reference 2. The curves traced in figure 1 are the average of the data from several complete mixture-response curves at each set of operating conditions. The power variations among the several curves at each set of operating conditions were negligible. The data for the full mixture-response curves are not shown.

RESULTS AND DISCUSSION

The reference-fuel framework covering tests at both operating conditions is presented in figure 2. From these figures cross plots were made (fig. 3) to facilitate conversion of the knock-limited indicated mean effective pressures of the test fuels to lead ratings. Figure 3 shows a definite irregularity in the lead susceptibility of the S-4 reference fuel particularly at the CRC cruise conditions; the region of irregularity exists from about 0.8 to 1.6 ml TEL per gallon. Because previous tests with almost the same equipment (references 1 and 2) had not shown the irregularity, a series of check tests were made with identical results. Numerous instances of this irregularity have been published, however, and a further investigation was not warranted at this time.

The knock-limited performance of the blends of the four aromatic hydrocarbons and the base fuel is presented in figure 4 and table I. All aromatic blends increased the knock-limited power of the base fuel at both operating conditions but the greatest improvement occurred at the CRC cruise conditions. The greatest increase in performance over the base fuel in the rich region at both operating conditions was obtained with the p-cymene blend. In the lean region at CRC cruise conditions (fig. 4(a)), p-cymene permitted the greatest improvement in knock-limited power over the base fuel whereas at the more severe conditions (fig. 4(b)), p-cymene and isobutylbenzene gave the best performance between fuel-air ratios of 0.06 and 0.075. At both operating conditions and all fuel-air ratios n-butylbenzene was the least effective of the four aromatics tested.

Figure 5 shows the knock-limited performance of the ether blends and the base fuel. All the ether blends show an improvement over the base fuel at both operating conditions. The methyl tert-butyl ether blend gave the greatest increase in knock-limited performance over the base fuel in the normal fuel-air-ratio range at both operating conditions; at fuel-air ratios leaner than 0.065 at the modified cruise conditions, however, ethyl tert-butyl ether gave an equal increase in knock-limited performance. At the CRC cruise conditions (fig. 5(a)) methyl phenyl ether was the least effective of the ethers tested in the fuel-air-ratio range from 0.062 to 0.11. At the more severe conditions (fig. 5(b)) methyl phenyl ether gave the smallest increase in knock-limited power over the base fuel between the fuel-air-ratio range from 0.0675 to 0.115 whereas in the extremely lean region (0.055 to 0.0675 fuel-air ratio) the blend of ethyl phenyl ether gave the smallest improvement in performance over the base fuel.

The tertiary butyl ethers gave higher ratings than the phenyl ethers except at very rich or very lean fuel-air ratios. The rating of methyl p-tolyl ether had a median value under the same conditions.

The data from figures 4 and 5 are incorporated in table I with the F-3, F-4, and full-scale cylinder ratings. The F-4 engine tests on the ether blends were incomplete and the data were unavailable for this report.

The correlation of the full-scale cylinder ratings of the aromatic blends with the F-4 ratings is shown in figure 6 on the basis of imep ratio (ratio of the imep of the test fuel to the imep of the base fuel). At either set of operating conditions the lean correlation is poor. The full-scale cylinder ratings are generally

higher than the F-4 ratings especially at the CRC cruise conditions (fig. 6(a)). The correlation of rich (0.10 fuel-air ratio) ratings are good at both operating conditions (fig. 6).

The correlation of the full-scale cylinder ratings of the aromatic blends with the F-3 ratings on the basis of performance number are shown in figure 7. The correlation is poor at both operating conditions and indicates the well known tendency of the F-3 engine to give low ratings to aromatic fuels.

Figure 8 presents the correlation between the full-scale cylinder ratings of the ether blends and the F-3 ratings in terms of performance numbers. The correlation at the modified CRC cruise conditions (fig. 8(b)) is slightly better than at the normal CRC conditions although neither is good. It is interesting to note that in the rating of the ether blends the F-3 engine gave higher ratings than the full-scale cylinder, indicating that the ether blends are less sensitive to engine conditions than the reference fuels.

SUMMARY OF RESULTS

Results of the knock tests on an aircraft-engine cylinder at two operating conditions are given in table I. The data indicate that:

1. The four aromatic hydrocarbons increased the knock limit of the base fuel at both operating conditions and p-cymene gave the greatest increase at all conditions with the exception of isobutylbenzene, which developed equivalent power in the lean region (0.06 to 0.075 fuel-air ratio) under the modified CRC cruise conditions.

2. The six ethers increased the knock-limited power of the base fuel at both operating conditions. Methyl tert-butyl ether gave the greatest increase throughout the normal fuel-air-ratio range at the CRC cruise conditions. Methyl tert-butyl ether also gave the

greatest improvement at the modified cruise conditions except at fuel-air ratios leaner than 0.065 where ethyl tert-butyl ether gave an equivalent increase in knock-limited performance.

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1. Jones, Anthony W., and Bull, Arthur W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. I - Eight Paraffins, Two Olefins. NACA ARR No. E4E25, 1944.
2. Bull, Arthur W., and Jones, Anthony W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. II - Twelve Aromatics. NACA ARR No. E4I09, 1944.

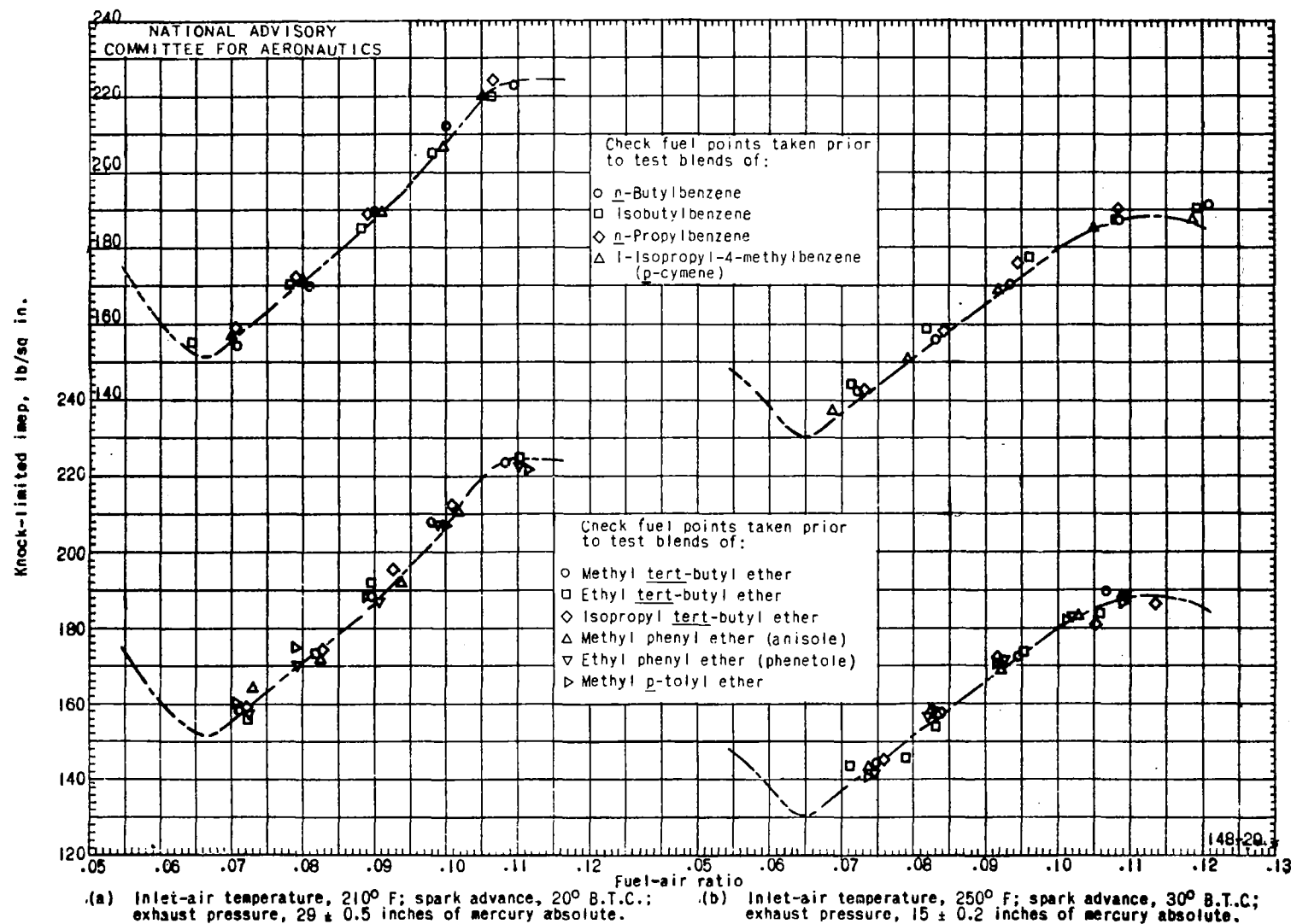
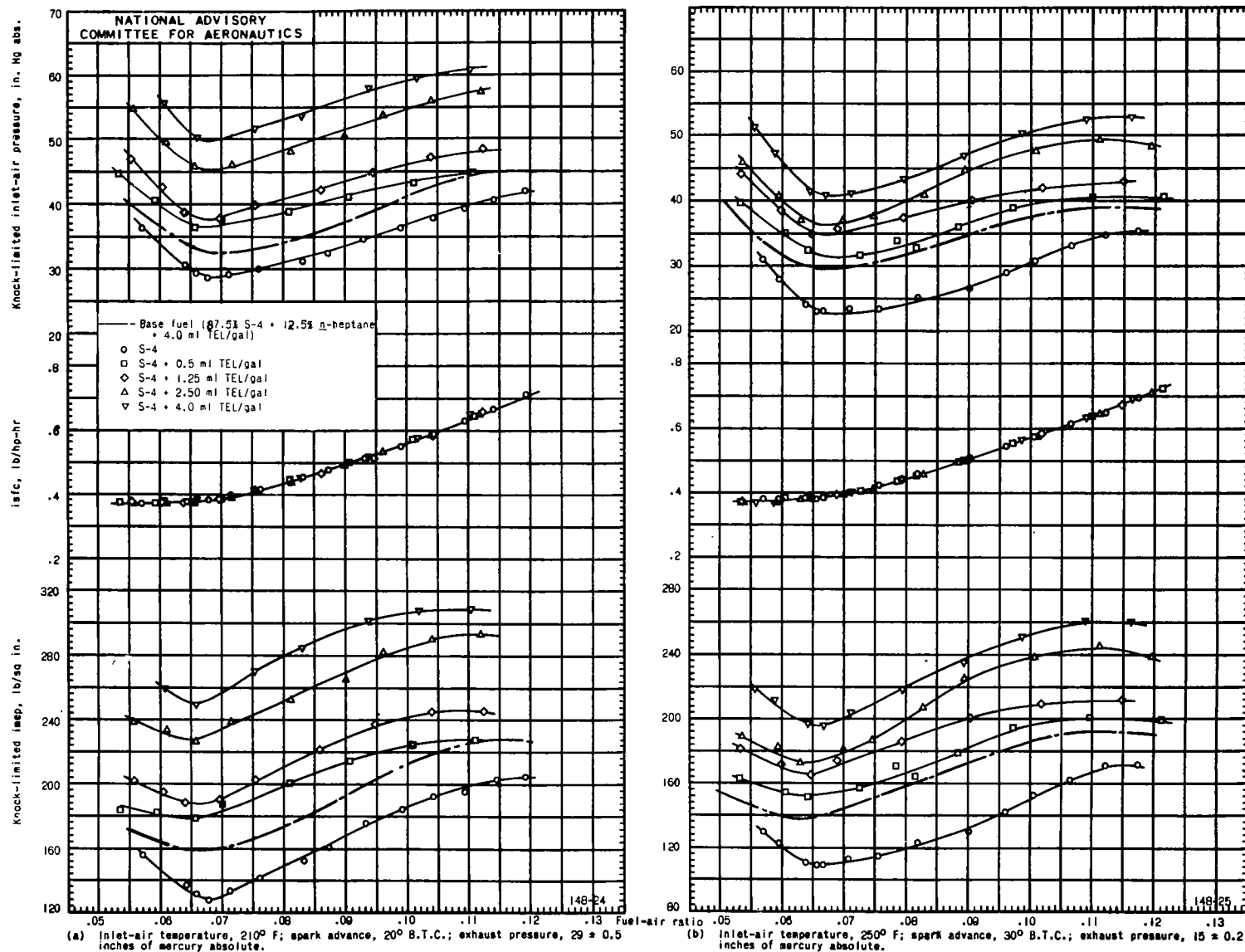


Figure 1. - Reproducibility of knock-limited indicated mean effective pressure with check fuel. Fuel, 85 percent S-4 and 15 percent M-4 plus 4 ml TEL per gallon; compression ratio, 7.3; engine speed, 2000 rpm. (Symbols represent check points for the various test fuels. The mixture-response curves shown are average curves in which the check runs are not included.)



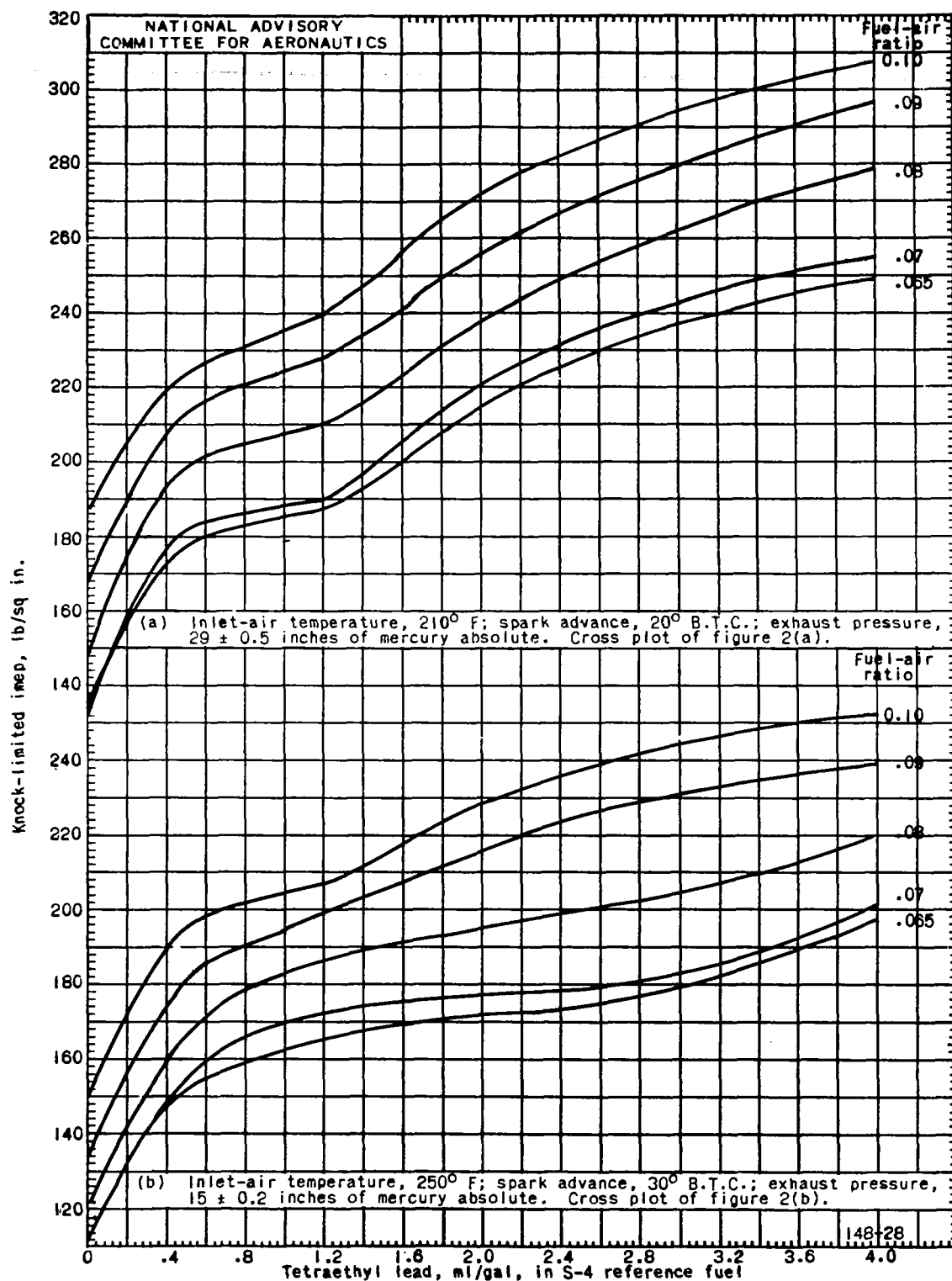


Figure 3. - Relation between knock-limited indicated mean effective pressure and lead concentration in S-4 reference fuel for different fuel-air ratios. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bme and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

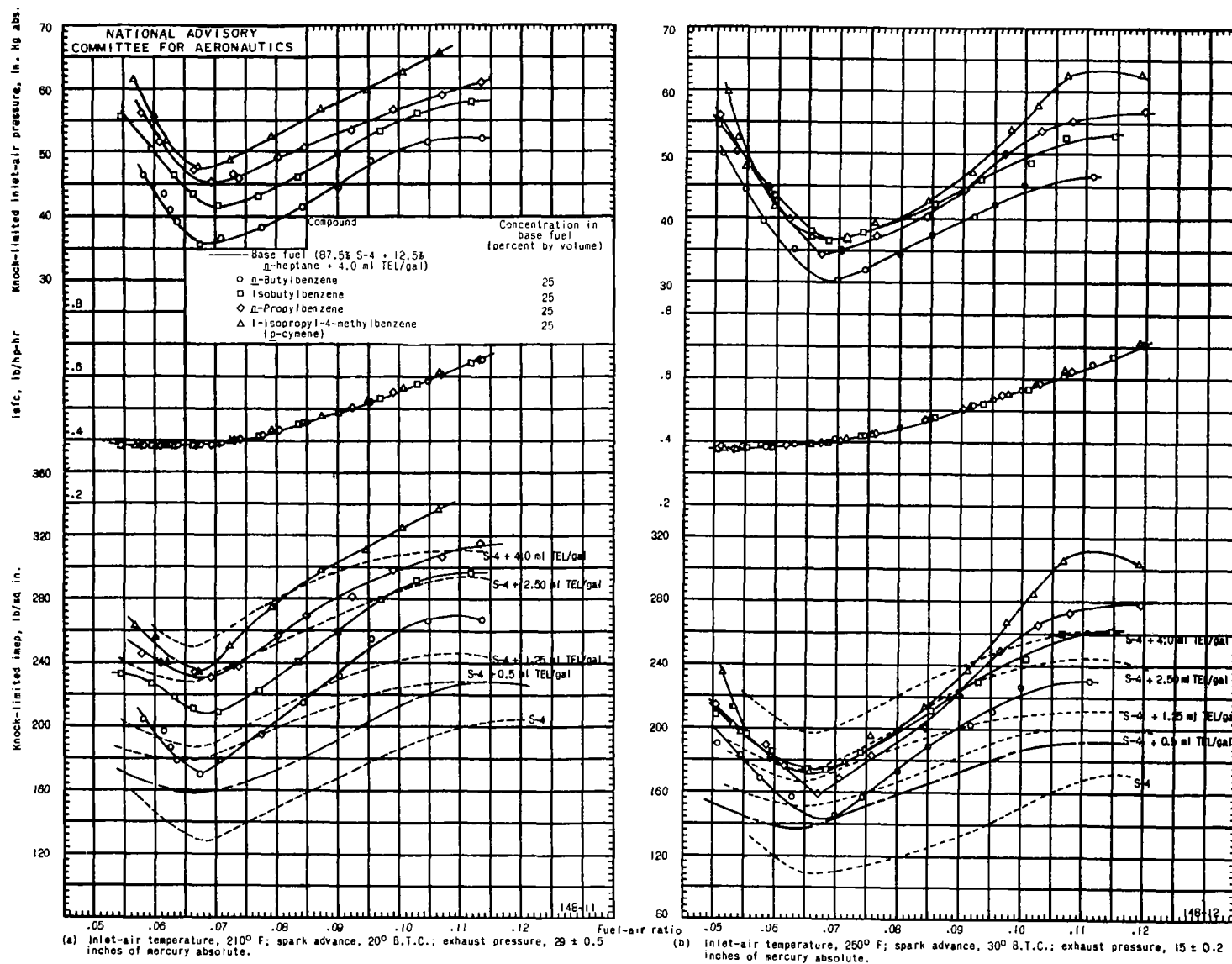


Figure 4. - Knock-limited performance of aromatic fuel blends. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmeq and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 355° F.

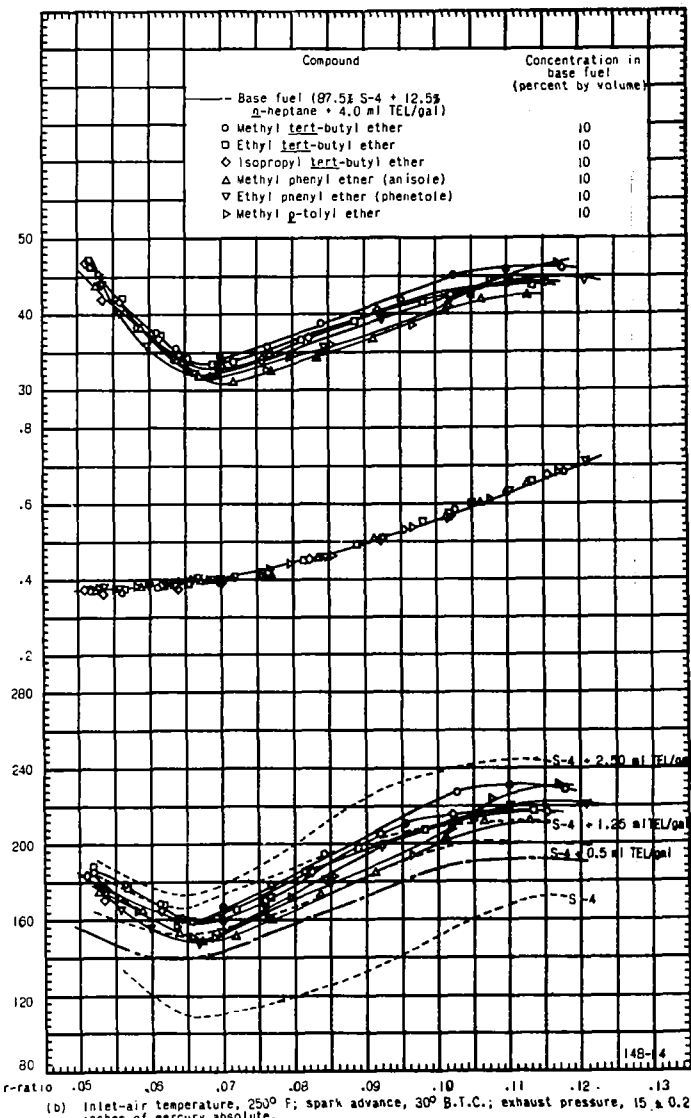
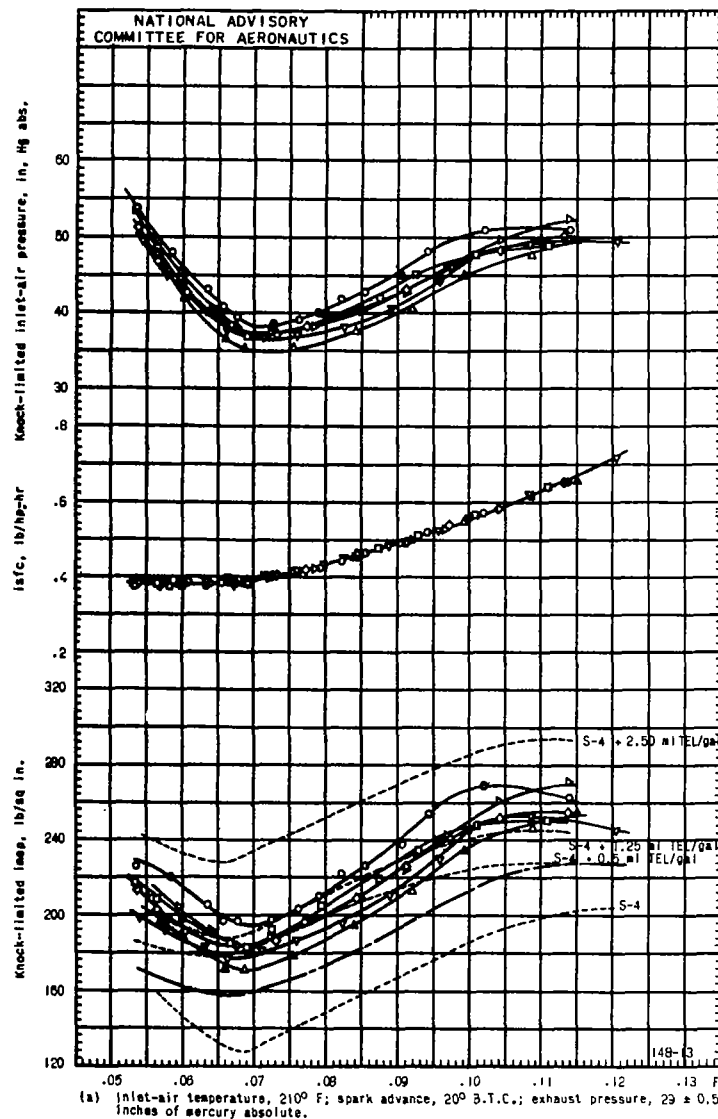
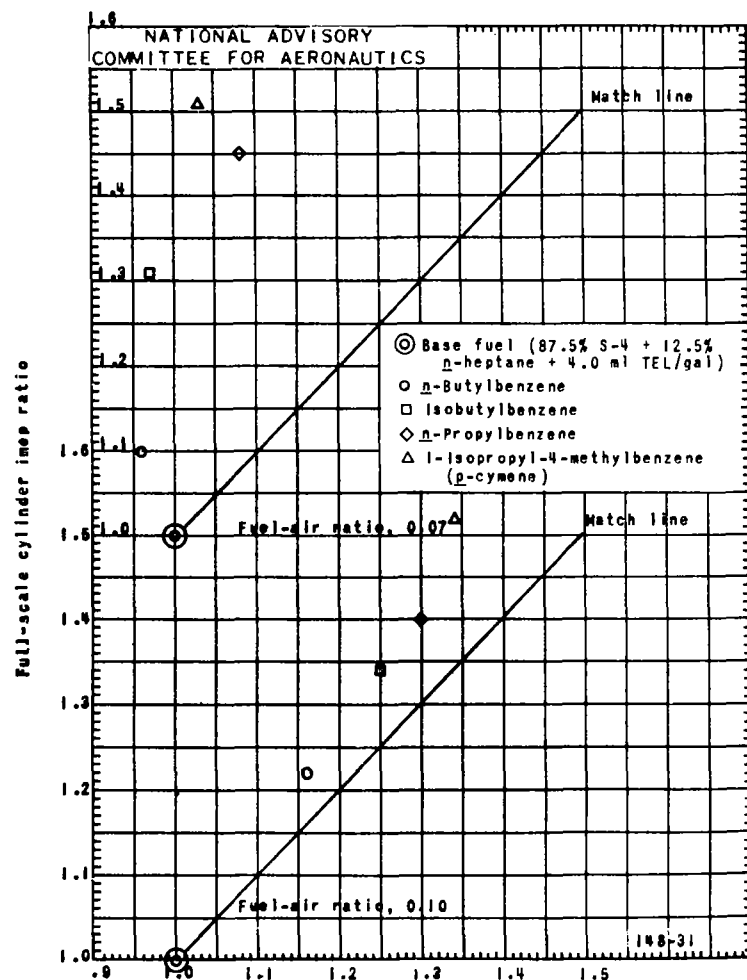
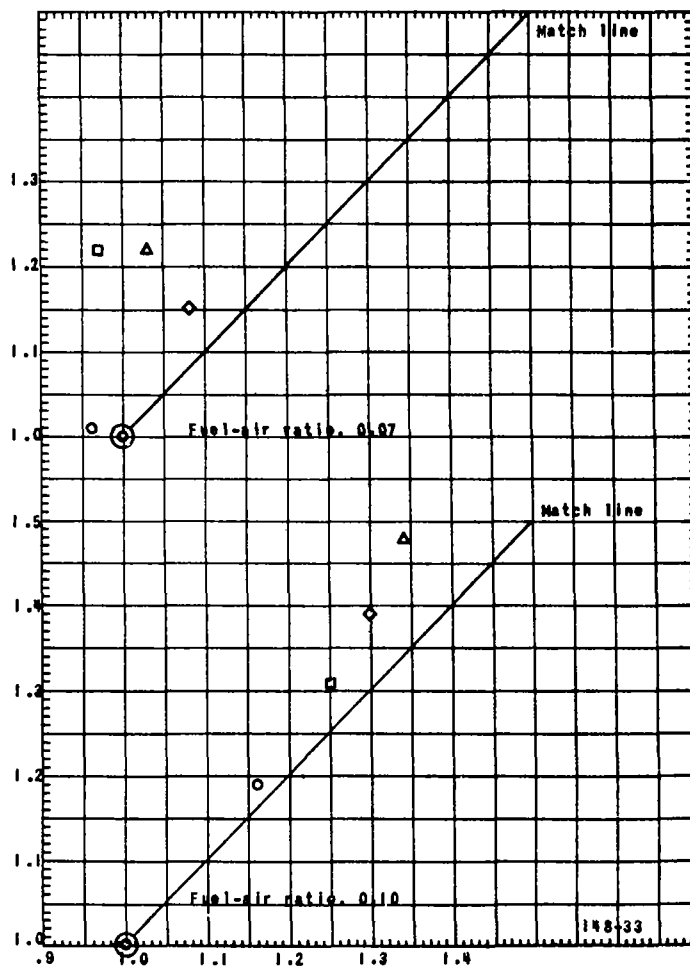


Figure 5. - Knock-limited performance of ether fuel blends. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bneq and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

Fig. 6



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.



(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

Figure 6. - Comparison of full-scale cylinder performance with F-4 engine performance. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmap and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

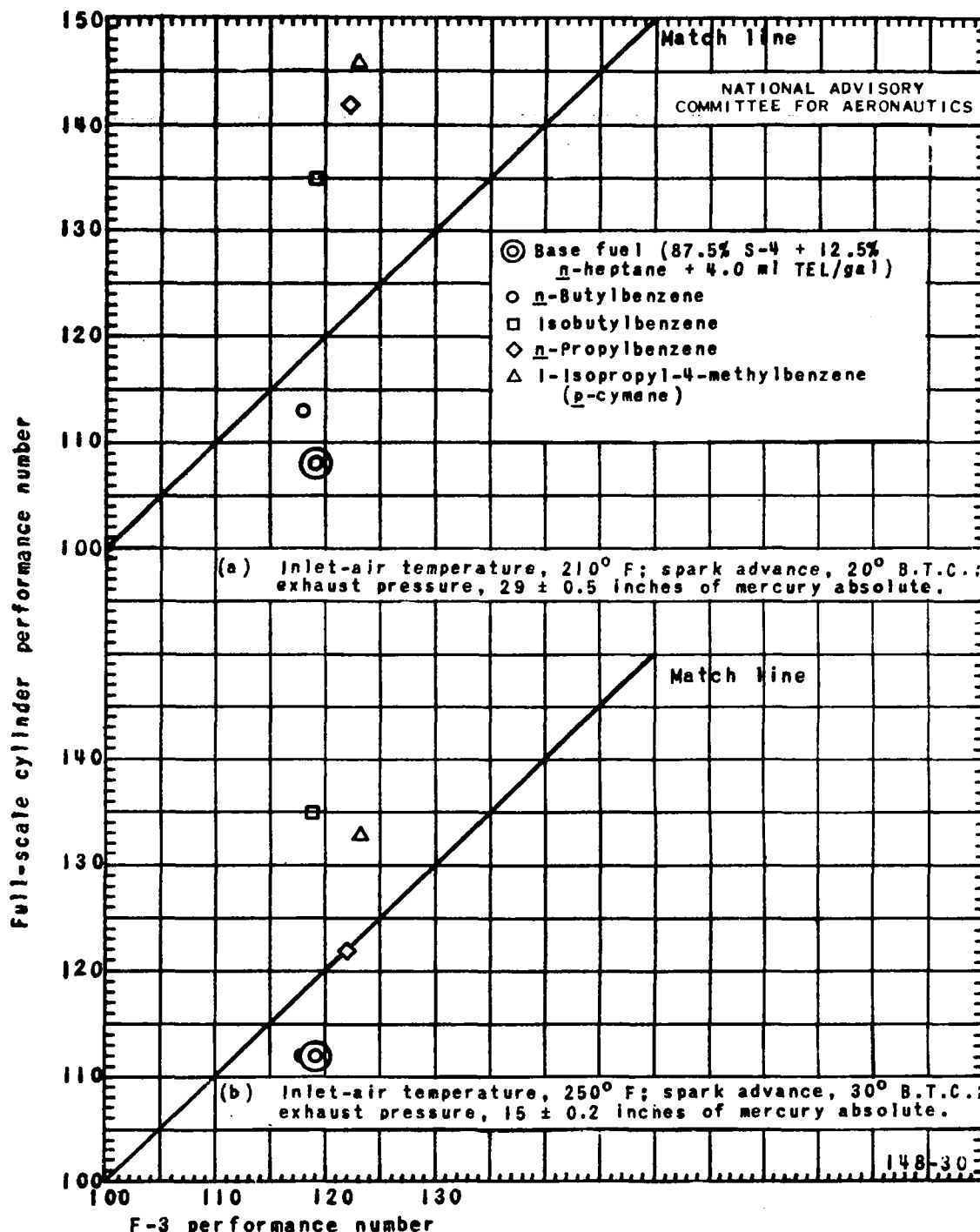


Figure 7. - Comparison of full-scale cylinder aromatic fuel-blend ratings with F-3 ratings. Fuel-air ratio, 0.07; compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmeP and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

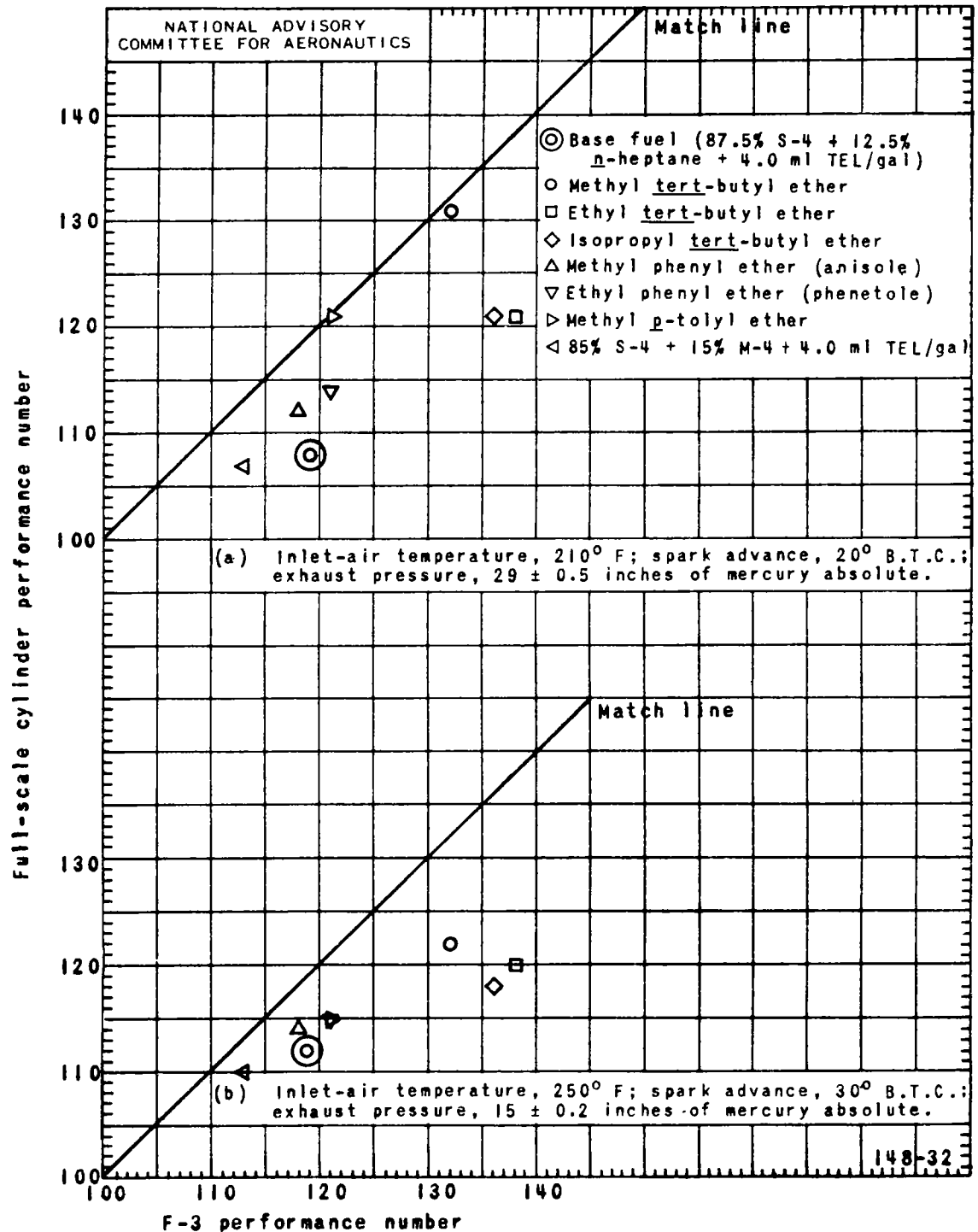


Figure 8. - Comparison of full-scale cylinder ether fuel-blend ratings with F-3 ratings. Fuel-air ratio, 0.07; compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmeq and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

TABLE I.- COMPARISON OF RATINGS OBTAINED IN A FULL-SCALE CYLINDER WITH F-3 AND F-4 RATINGS

[For each compound there are four rows of values. The first row is imep, lb/sq in.; the second is tetraethyl lead in S reference fuel, ml/gal, except as noted; the third is performance number; and the fourth is ratio of imep of blend to imep of base fuel]

Compound	Concentration in base fuel (percent by volume)	F-3 ratings	F-4 ratings	Full-scale cylinder ratings (compression ratio, 7.3; engine speed, 2000 rpm)											
				Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ±0.5 inches mercury						Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ±0.3 inches mercury					
				Fuel-air ratio			Fuel-air ratio			Fuel-air ratio			Fuel-air ratio		
				0.070	0.100	0.11	0.065	0.07	0.08	0.09	0.10	0.065	0.07	0.08	0.09
n-Butylbenzene	25	----- 0.60 118 -----	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	120 200 204 176 176 203 233 260 147 146 175 202 222	
Isobutylbenzene	25	----- 0.64 119 -----	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	114 213 222 197 167 177 216 2.54 2.60 1.64 2.20 2.36 3.04 147 147 131	
n-Propylbenzene	25	----- 0.80 122 -----	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259	136 227 240 232 232 256 281 299 165 166 192 223 259
1-Isopropyl-4-methylbenzene (p-cymene)	25	----- 0.82 123 -----	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276	132 231 248 238 241 277 303 323 173 175 200 233 276
Methyl tert-butyl ether	10	----- 1.45 132 -----	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136	134 131 130 137 123 128 136 136
Ethyl tert-butyl ether	10	----- 1.96 138 -----	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131	129 121 130 132 127 125 131 131
Isopropyl tert-butyl ether	10	----- 1.75 136 -----	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213
Methyl phenyl ether (anisole)	10	----- 0.60 118 -----	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127	115 112 111 114 127 127 127 127
Ethyl phenyl ether (phenetole)	10	----- 0.75 121 -----	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111	117 114 113 111 111 111 111 111
Methyl p-totyl ether	10	----- 0.75 121 -----	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116	130 121 116 116 116 116 116 116
Base fuel ^a (87½ S-4 + 12½ n-heptane + 4.0 ml TEL/gal)		----- 0.63 119 -----	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213	126 171 174 158 160 173 192 213
85% S-4 + 15% M-4 + 4.0 ml TEL/gal ^d		----- 0.39 113 -----	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180	152 156 171 187 208 130 137 151 166 180

^aPercentage S-4 reference fuel + 4.0 ml TEL/gal in n-heptane reference fuel + 4.0 ml TEL/gal.

^bBased on imep data of base fuel check curves taken with each test fuel.

^cBase fuel used for blending compounds.

^dBase fuel used in references 1 and 2 and for checking engine conditions.

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